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Contributions of Space Geodesy to Geodynamics:
Earth Dynamics

Atmospheric Excitation of the Earth's Rotation: Progress and Prospects Via Space Geodesy

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Investigations into the Earth's angular momentum budget and research into solid Earth-atmosphere interactions have been revolutionized by the advent of modern space geodetic measurements of the Earth's rotation. These advances have been accompanied by improvements in measurements and numerical models of the Earth's global atmosphere, which are used to calculate values of atmospheric angular momentum and other synergistic atmospheric data sets. Recent progress, as well as international cooperation through MERIT, the IERS and the IUGG/IAG Special Study Group 5-98 (Atmospheric Excitation of the Earth's Rotation), are described here together with anticipated advances and prospects for the future.

I. INTRODUCTION

The study of the Earth's orientation in space (this term is defined to include the phenomena of Earth rotation, polar motion, precession and nutation) encompasses the complex nature of orientation changes, the excitation of these changes and their geophysical implications in a broad variety of areas. Earth system studies have embarked on a new era with the advent of highly accurate space geodetic techniques and the availability of complementary geophysical data sets. Techniques utilized include laser ranging to the Moon and artificial satellites (LLR and SLR), very long baseline interferometry (VLBI) and the newly developing GPS technology. The measurements reveal minute but complicated changes of up to several parts in 10^8 in the speed of the Earth's rotation, corresponding to several milliseconds in the length of the day (LOD; see Fig. 1). Intercomparisons indicate that Earth rotation is routinely determined at the 0.03 millisecond (ms) level for UT1 (approximately ~1.4 cm at the equator) and 0.3 milliarcseconds (mas) for polar motion (approximately 1 cm) [Gross, 1992], with higher accuracy being achieved in some cases. Many geophysically interesting variations are detectable at these levels. The analysis and understanding of these phenomena draws upon and contributes to the fields of meteorology, oceanography, astronomy, celestial mechanics, seismology, tectonics, and geodynamics.

Contributions of Space Geodesy to Geodynamics: Earth Dynamics
Geodynamics 24

Changes in Earth orientation are caused by variations in the inertia tensor of the solid Earth due to deformation and by exchanges of angular momentum between the solid and fluid parts of the Earth, as well as by exchanges of angular momentum with extraterrestrial objects. Changes in Earth rotation and polar motion can be regarded as the response of a linear differential system to a three-dimensional excitation vector. Earth rotation, when studied in combination with other parameters such as global integrated atmospheric angular momentum (AAM) and the Southern Oscillation Index, allows new and unique insights into geophysical processes. From intercomparisons of AAM and LOD (Fig. 2), we find that Earth rotation variations over time scales of a few years or less are dominated by atmospheric effects, with a dominant seasonal cycle and significant variability on the intraseasonal (40 to 50 day) time scale. Variations on interannual time scales have been related to the El Niño/Southern Oscillation phenomenon. Torques between the core and mantle are the most probable cause for the longer-scale "decade" fluctuations in the LOD (see for example, Hide, 1989 and Jault and Le Mouël, 1991). Trends found on even longer time scales (the "secular" changes) are due to tidal dissipation torques, which produce a steady increase in the LOD at a rate estimated from ancient eclipse records to lie between 1 and 2 milliseconds per century. Contributions to LOD changes on the same time scale are also produced by internal sources, such as changes in the moment of inertia of the solid Earth resulting from the melting of ice after the last glacial maximum.

Polar motion consists mainly of nearly circular oscillations at periods of one year (the annual wobble) and about 433 days (the Chandler wobble), with amplitudes of about 100 and 200

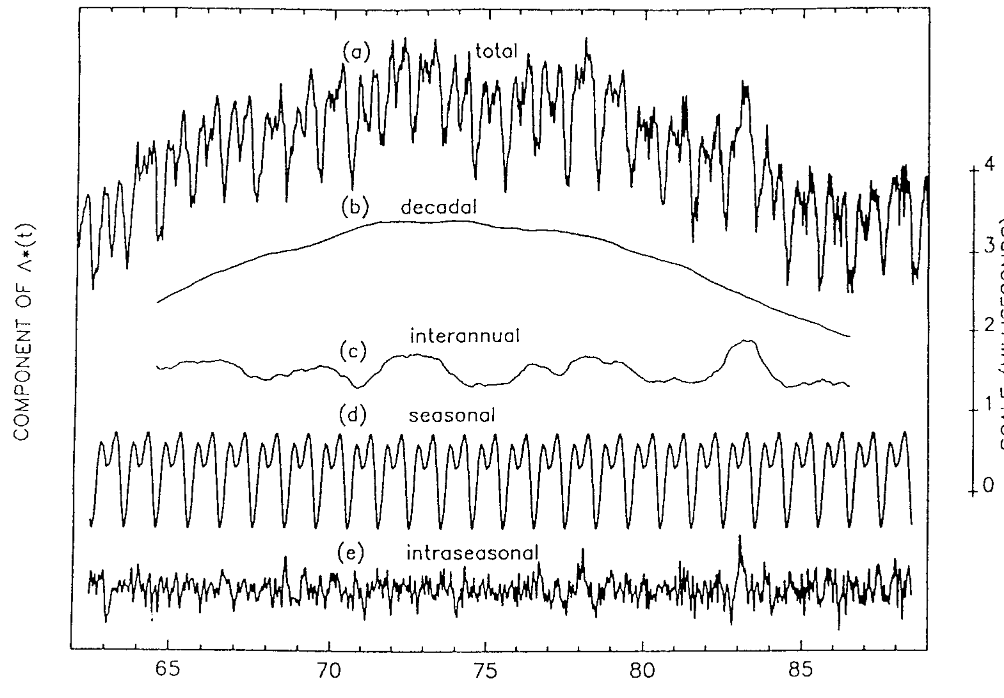

Fig. 1. Time series of irregular fluctuations in the length of the day $\Lambda(t)$ from 1963 to 1988 (curve a) and its decadal [$\Lambda_\alpha(t)$], interannual [$\Lambda_\beta(t)$], seasonal [$\Lambda_\gamma(t)$ and intraseasonal [$\Lambda_\delta(t)$ components (curves b, c, d and e, respectively). The component $\Lambda_\alpha(t)$] largely reflects angular momentum exchange between the solid Earth and the underlying liquid metallic outer core produced by torques acting at the core-mantle boundary. The components $\Lambda_\beta(t)$, $\Lambda_\gamma(t)$ and $\Lambda_\delta(t)$ largely reflect angular momentum exchange between the atmosphere and the solid Earth, produced by torques acting directly on the solid Earth over continental regions of the Earth's surface and indirectly over oceanic regions; after Hide and Dickey [1991].

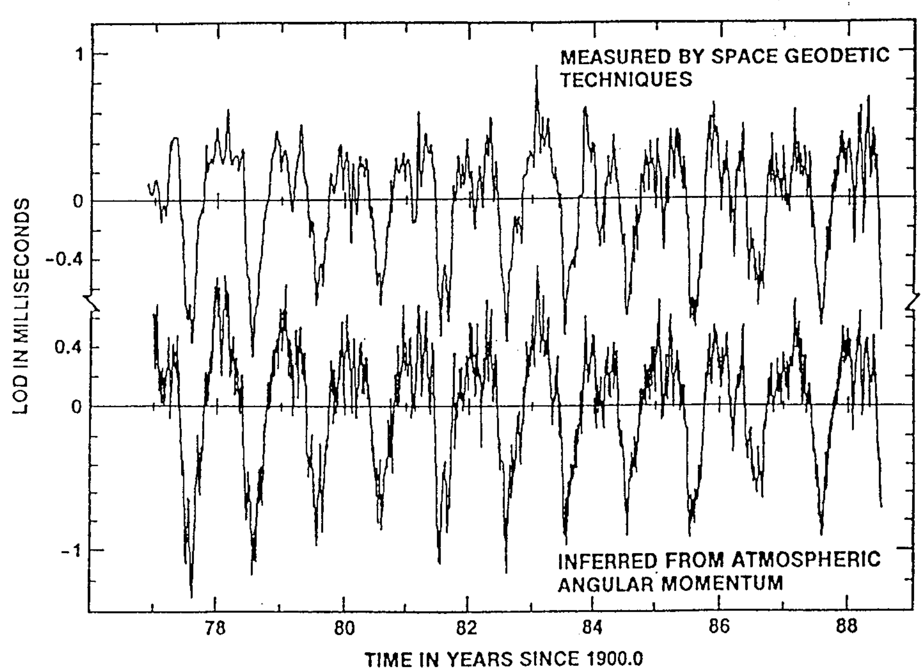

Fig. 2. Time series of the sum of the seasonal and intraseasonal LOD components [see Fig. 1], with the upper curve measured by space geodetic techniques and the lower curve inferred from routine daily determinations of changes in the axial component of the atmospheric angular momentum made by the U. S. National Meteorological Center.

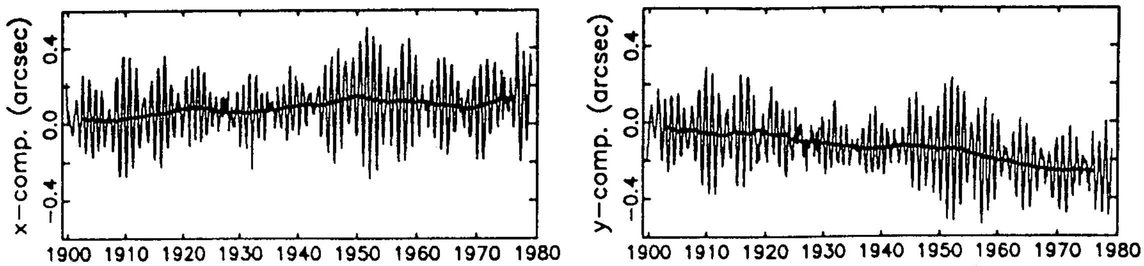

Fig. 3. Polar motion, 1900-1980, after Gross [1990].

milliarcseconds (mas), respectively, together with a long-term drift of a few milliarcseconds per year (Fig. 3). In addition, analysis of geodetic data reveals rapid polar motion, with peak-to-peak variations of approximately 2 to 20 mas, fluctuating on time scales between two weeks and several months (Fig. 4). Comparisons with meteorological data suggest that these latter motions are at least partially driven by surface air pressure changes, as modified by the response of sea level to atmospheric loading [Eubanks et al., 1988].

This paper highlights advances in Earth orientation, focusing on studies of short-period fluctuations made possible by the space geodetic techniques, and stresses the important role of international cooperation in recent and future progress. The second section describes the enabling space geodetic techniques as well as the synergistic atmospheric data types, while the third section addresses international cooperation through MERIT (Monitor Earth Rotation and Intercompare the Techniques of Observation and Analysis), IERS (International Earth Rotation Service) and IUGG/IAG Special Study Group 5-98 (Atmospheric Excitation of the Earth's Rotation). Section 4 highlights recent advances in analysis and interpretation. The final section presents a summary and prospects for the future.

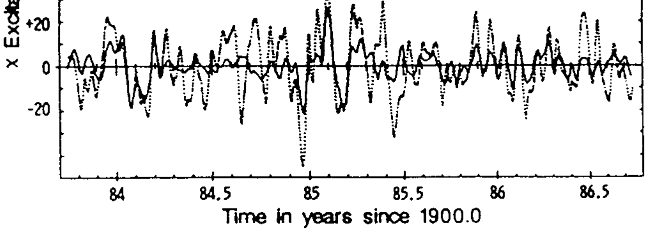

Fig. 4. Kalman smoothed estimated of the NMC χ(land) data, from the pressure term, together with the Kalman deconvolved geodetic χ(dotted lines) after seasonal adjustment; after Eubanks et al. [1988].

The reader is referred to several more detailed accounts of the excitation of Earth orientation changes. References to early work can be found in the classical monograph on the subject by Munk and MacDonald [1960] and to more recent work in various monographs and other publications [e.g., Cazenave, 1986; Dickey and Eubanks, 1986; Eubanks, this volume; Hide, 1977, 1984, 1986 and 1989; Hide and Dickey, 1991; Lambeck, 1980 and 1988; Moritz and Mueller, 1987; and Wahr, 1988].

II. ENABLING SPACE GEODETIC MEASUREMENTS AND SYNERGISTIC ATMOSPHERIC DATA

A. *Geodetic Observations and Measurements*

The modern measurement types include GPS (Global Positioning System), lunar laser ranging (LLR), satellite laser ranging (SLR) and very long baseline radio interferometry (VLBI). Improvements in the observing systems (hardware, software and the development of well-distributed global networks) have lead to dramatic improvements in the determination of the Earth orientation parameters. For example, estimates of a combined Kalman series utilizing the modern space techniques of LLR, SLR and VLBI have uncertainties in polar motion and universal time (UT1) at the ~2 mas (6 cm) and the 0.5 ms (~23 cm) level, respectively, for the late 1970s, whereas current uncertainties have improved to 0.3 mas for polar motion and 0.03 ms for UT1 [Gross, 1992]. There has also been an impressive increase in time resolution. The classical optical technique, utilizing a global network of more than 50 observatories, obtained UT1 at the millisecond level at 5-day intervals [Feissel, 1980]; in contrast, the VLBI Extended Research and Development Experiment (ERDE) obtained sub-hourly measurements of both UT1 and polar motion [Clark et al., 1990; Herring and Dong, 1991].

In each of these techniques, changes in Earth orientation are monitored by observing extraterrestrial objects from the surface of the Earth. The observed objects are used to approximate a nonrotating reference frame, either directly in the case of slow-moving objects, or from dynamical theories of their motion, in the case of planetary and satellite observations. In each case, Earth orientation is estimated from the apparent motion of the Earth with respect to this frame. The measurement types are summarized briefly below. The reader is referred to several articles in this volume which treat each technique in more detail, and to the International Earth Rotation Service Annual Report for a compilation and a brief description of the available data and associated analyses.

Lunar Laser Ranging. Lunar laser ranging (LLR) data consist of estimates of the round-trip time of flight of laser pulses from terrestrial observatories to retroreflectors placed on the Moon's surface by the Apollo astronauts and by unmanned probes from the Soviet Union. Lunar laser ranging can provide monitoring of Universal Time with a temporal resolution shorter than a day. The ability to model accurately the lunar orbit since the first observations in 1969 allows the determination of the Earth's nutations and long-term studies of variations in Universal Time, as well as the determination of many parameters of the Earth-Moon system. One asset of LLR is its ability to provide rapid determinations of the Earth's rotation; a determination can literally be made as the Moon sets. The current network consists of two observatories: McDonald Observatory (Texas), and CERGA in southern France near Grasse.

Satellite Laser Ranging (SLR). In this technique, very short laser-generated pulses of light are transmitted to retroreflectors mounted on the surface of artificial satellites; the round-trip travel times of these pulses (and hence the path lengths) are measured. A series of SLR measurements from a global network of about twenty stations permits the determination of orbital parameters, a satellite ephemeris and relative station locations. High-quality Earth rotation data, as well as other quantities of geophysical interest (e.g., plate motion and gravitational studies), are generated by SLR. The best geodetic data come from laser ranging to the LAGEOS (Laser Geodynamics Satellite) target, a dense sphere placed in a high (6000 km) orbit. The orbit of this satellite can be used as a nonrotating reference system only for periods short compared to a year. Because polar motion induces a diurnal residual motion of an observatory (as seen from a nearly inertial reference frame), the stability of the LAGEOS orbit is sufficient to provide highly accurate and stable polar motion estimates, while LAGEOS UT1 estimates diverge from the true UT1 after a few months. The LAGEOS data are used, however, in studies of high-frequency changes in UT1 or LOD. LAGEOS determinations of polar motion and Earth rotation rate variations are currently made routinely every three days.

Very Long Baseline Interferometry (VLBI). Radio interferometry is currently used to make highly accurate measurements of UT1, the orientation of the Earth's axis in space (nutation and precession), and polar motion with observing times of less than an hour to a day. VLBI measures the interferometric group delay, i.e., the difference in the time of arrival of a radio signal at two or more radio telescopes. The delay rate (the time derivative of the interferometric phase delay) is generally measured as well. The interferometric delay between two telescopes is a direct estimate of the projection of the baseline vector (the vector between the telescopes) in the direction of the radio source. Observations from one baseline are thus not sensitive to rotation about that baseline. For single-baseline results (two stations), two components of Earth orientation are determined and can be related to local universal time (UT0) and the variation of latitude. Multibaseline VLBI can measure all three components of the Earth orientation if some of the baselines are nonparallel. Regular independent VLBI estimates of Earth orientation are now produced routinely twice per week with UT0 determined daily.

Global Positioning System (GPS). The GPS technology is the newest space geodetic technique to be utilized in the determination of Earth rotation and polar motion and is an area of intense interest and activity [see Blewitt, this volume]. A large constellation of satellites (15 in current operation with plans for 24) transmitting at microwave frequencies together with a globally distributed network of receivers permits the determination of polar motion as well as changes in UT1. Polar motion induces a diurnal residual motion of a site (as seen from a nearly inertial reference frame), which is readily separable from expected perturbations of the satellite constellation, thus allowing for robust determination. GPS, like other Earth orbiters such as LAGEOS, in general, cannot determine an absolute estimate of UT1, which is tied fundamentally to the celestial sphere. The long period evolution of the node of a satellite orbit due to nongravitational forces and changes in the gravitational field of the Earth eventually causes the UT1 series produced by Earth orbiters to drift from the true UT1, as obtained from an inertial source (either VLBI or lunar laser ranging). In addition, drifts are also produced by stochastic variations in the mass distribution of the Earth's atmosphere and hydrosphere. Hence, satellites are sensitive to changes in UT1 and must be initially tied to an inertial source of UT1 and must be periodically corrected and updated. Like LAGEOS, GPS results are very useful in the determination of high-frequency changes in UT1 or LOD.

B. Synergistic Atmospheric Data

Fluctuations in the rotation of the solid Earth over time scales of less than about 5 years are dominated by atmospheric effects. Changes in atmospheric winds and the distribution of surface pressure cause variations in the atmospheric angular momentum (AAM). Many detailed studies of Earth rotation fluctuations and of compensating AAM fluctuations have been reported in the past decade. Research in this area has been facilitated by the use of the dimensionless atmospheric angular momentum (AAM) functions χ_i (i = 1, 2, 3). In this scheme the excitation of polar motion is determined by $\chi_1(t)$ and $\chi_2(t)$, and that of axial rotation variation by $\chi_3(t)$. It is the χ_i functions that are issued routinely by meteorological agencies. The three components are given by:

$$\chi_1 = \frac{-1.00R^4}{(C-A)g}\iint P_s \sin\phi\cos^2\phi\cos\lambda\, d\lambda d\phi - \frac{1.43R^3}{\Omega(C-A)g}\iiint (u\sin\phi\cos\phi\cos\lambda - v\cos\phi\sin\lambda)\, d\lambda\, d\phi\, dp$$

$$\chi_2 = \frac{-1.00R^4}{(C-A)g}\iint P_s \sin\phi\cos^2\phi\sin\lambda\, d\lambda\, d\phi - \frac{1.43R^3}{\Omega(C-A)g}\iiint (u\sin\phi\cos\phi\sin\lambda + v\cos\phi\cos\lambda)\, d\lambda\, d\phi\, dp$$

$$\chi_3 = \frac{0.70R^4}{Cg}\iint P_s\cos^3\phi\, d\lambda\, d\phi + \frac{R^3}{C\Omega g}\iiint u\cos^2\phi\, d\phi\, d\lambda\, dp \quad (1)$$

where Ω is the mean angular speed of the rotation of the solid

TABLE 1. Atmosphere Data Sets Archived at IERS Sub-Bureau for Atmospheric Angular Momentum

Analysis Parameters	Specification
AAM Equatorial χ_1, χ_2 AAM Axial χ_3	Hemispheric values for wind, pressure and pressure + inverted barometer (ib)
Zonal Mean Zonal Winds [u] Zonal Mean Temperatures [T]	5° latitude intervals, 12 mandatory pressure levels
Mean Surface Pressure	Global average
Surface Pressure Coefficients	Triangular truncation to wave 4 zonals only to wave 20
Forecast Parameters	**Specification**
AAM Equatorial χ_1, χ_2 AAM Axial χ_3	Global forecast values at 12-h intervals to 10 days for wind, pressure, pressure + ib

After Salstein and Kann, 1992

Earth, (ϕ, λ) denote latitude and longitude respectively, $p_s(\phi, \lambda, t)$ is the surface pressure, $u(\phi, \lambda, p, t)$ represents the eastward (westerly) component of the wind velocity at the pressure level p, $v(\phi, \lambda, p, t)$ is the corresponding meridional wind, R is the mean radius of the Earth (6.37 x 10^6 m), g = 9.81 m s^{-2} is the mean acceleration due to gravity, and C and A are the axial and equatorial moment of inertia of the solid Earth respectively [Barnes et al., 1983]. The numerical coefficients incorporate the so-called "Love-number" correction, which allows for concomitant changes in the inertia tensor of the imperfectly-rigid solid Earth.

Routine daily or twice-daily determinations of χ_i are now produced at four meteorological forecasting centers (Tables 1 and 2): the European Centre for Medium-range Weather Forecasts (ECMWF—series begins December 1979), the Japan Meteorological Agency (JMA—series originating in September 1983), the U. K. Meteorological Office (UKMO—commencing in May 1983), and the U. S. National Meteorological Center (NMC–series starting in January 1976). Several atmospheric variables, including the surface pressure and the vertical distribution of the horizontal components of the wind velocity vector, are estimated at each model grid point. The grid point data are updated several times daily by means of a forecast assimilation scheme, in which weighted means of data from the earlier forecast and new observational values are used [McPherson et al., 1979]. The model's predictive scheme is used to estimate grid point values over regions with sparse data coverage. Reliance on model forecasts in regions such as the South Pacific with continually sparse coverage could introduce systematic errors in the resulting excitation estimates. Changes in the angular momentum of the atmosphere are archived at 12- or 24-h intervals (depending on the service used) from the appropriate volume integral over the whole atmosphere.

TABLE 2. Availability of Atmospheric Data from Meteorological Centers

	ECMWF	JMA	NMC	UKMO
Analyses				
χ^W	*[a]	*	*[a,b]	*[a]
χ^P	*	*	*	*
χ^P(IB)		*	*	
[u]	*		*[c]	
[T]	d		*	
p-harmonics			*	
Forecasts				
χ^W, χ^P	3, 5, 10 days		1-10 days	1-6 days
[u]			1-10 days	

a—available in near-real time
b—χ_3^W also available to 100 mb
c—including alternated world ocean formulations
d—through 1990 only

Adapted from Salstein et al., 1992

The AAM changes can be divided into two categories: changes in the net atmospheric rotation rate [the wind term represented by second integral in Eq. (1)] and changes in the net atmospheric moment of inertia (the pressure term represented by the first integral). These terms can be decoupled to first order and are generally calculated separately. The dominant contribution to fluctuations in χ_3 [and to the compensating fluctuations in LOD] originates from the wind term, with the pressure term generally contributing no more than about 10%. The calculation of the wind terms involves an integration over the atmosphere, with the maximum height considered dependent on the model(s) used at the center. In order to account for fluctuations in the total angular momentum of the atmosphere, one would like to integrate to the highest level possible; the realization that various centers integrate to different levels complicates intercomparison studies. The pressure term is important in polar motion variations. A rough allowance for the response of the oceans to atmospheric surface pressure changes can be made by the inverted barometer (IB) correction, which assumes that the oceans are able to reach equilibrium immediately with atmospheric surface loading [Barnes et al., 1983]. The effect of the IB correction is quite large, being comparable in size to the term itself; the degree to which the ocean responds as an IB is an open question which is under current study [Ponte et al., 1991]. Hence, it is desirable to archive two series (assuming both non-IB and IB response of the oceans). Data are also archived as hemispheric as well as global integrals. Because of the dominance of atmospheric effects in short period Earth rotation variations and the need for accurate real-time predictions, forecasts of zonal mean zonal winds [u] and the full three-dimensional vector of the χ functions are also calculated and archived (see Tables 1 and 2 and Section III).

Additional atmospheric quantities related to global variations also are of geophysical interest, and are archived (Tables 1 and 2, Salstein et al., 1992). Zonal mean zonal winds [u], calculated in equal area latitude belts, have proven to be invaluable in studying regional contributions to global phenomena [Rosen and Salstein, 1983; Rosen et al., 1991; Dickey et al., 1992a] and for investigating AAM propagation [Dickey et al., 1991 and 1992a]. Zonal mean temperatures [T], whose gradients are related to the wind term in particular and the global circulation of the atmosphere in general, are provided by the NMC as well. The mean surface pressure and a set of the low-order surface pressure spherical harmonics are also archived. One particular motivation here is that satellites are affected by the varying gravitational field caused by the redistribution of atmospheric mass (see for example, Schutz et al., 1989, Chao and Au, 1991a).

III. Progress Via International Cooperation

The advances in space geodesy has created the potential for further profound advances and has led to a number of national and international programs to promote the collection and analysis of data from all techniques. In the late 1970s, it became evident that the new space geodetic techniques had the power and potential to revolutionize Earth rotation studies; in particular, techniques such as laser ranging and VLBI had the promise to provide an order of magnitude improvement in data accuracy. The very nature of space geodesy, for example, the need for global laser ranging and VLBI networks, requires a well coordinated international program. A working group, jointly sponsored by the International Union of Geodesy and Geophysics (IUGG) and the International Astronomical Union (IAU), was formed in 1978 to investigate the capabilities of the new techniques, intercompare results from both new and traditional optical techniques and to make recommendations for future activities [Mueller and Wilkins, 1986]. This working group was appropriately named MERIT [an acronym for Monitor Earth Rotation and Intercompare the Techniques of Observation and Analysis].

The MERIT working group, in addition to benchmarking the space techniques and intercomparing results, was also very interested in the scientific analysis and implications of the improved observations. Various studies had demonstrated that angular momentum transfer between the atmosphere and the solid Earth is the dominant cause of short-term variations in the LOD; understanding the transfer of angular momentum in the atmosphere/solid Earth/ocean system is a problem of great scientific importance and remains a focus of intense activity. It was recognized that regular and accurate determinations of the angular momentum of the atmosphere were vital for the scientific analysis and interpretation of MERIT data. To this end, an IUGG/IAG Special Study Group, 5-98—Atmospheric Excitation of the Earth's Rotation—was established in 1983 [Dickey, 1984 and 1989]. The foremost objectives of this study group can be summarized into three main thrusts:

(i) Encourage multidisciplinary studies on the transfer of angular momentum among the oceans, atmosphere, and solid Earth, and the resulting contribution to variations in the length of day and changes in polar motion; consider the hydrospheric influences (sea level changes and ground water storage) on the Earth's rotation;

(ii) Strive for improved communication and data flow between the atmospheric and geodetic communities; continue and improve the existing data base and the associated documentation, and stress greater interaction on models and applications of results;

(iii) Advocate improvements in the measurement techniques and interface with the meteorological centers to provide the best possible atmospheric data sets, especially during the special MERIT measurement campaign.

The success of MERIT was truly outstanding, with its campaigns clearly demonstrating the superiority of the space geodetic techniques relative to the classical optical techniques. During its main campaign (September 1983-October 1984), the space techniques yielded the most accurate Earth rotation data collected to that date. Daily [Eanes et al., 1984] and even sub-daily [Robertson et al., 1985] values of Earth rotation within accuracies well below the millisecond level were reported during the intensive part of the MERIT campaign (April-June 1984); daily polar motion determinations were also obtained during this period [Eanes et al., 1984 and Tapley et al., 1985a and b]. These highly accurate measurements, analyzed together with atmospheric angular momentum data, allowed new and important insights into solid Earth-atmosphere interactions and the Earth's angular momentum budget. Based on the MERIT legacy, a new service, the International Earth Rotation Service (IERS, centered in Paris) was formed to consolidate the earlier activities of the BIH (Bureau International de l'Heure, based in Paris) for determining Earth rotation (UT1 and LOD), and of the International Polar Motion Service (based in Japan) for determining polar motion (PM). The IERS began its activities in January 1988, with its products being based primarily on the space geodetic techniques of laser ranging to the moon and artificial satellites and Very Long Baseline Interferometry [Mueller and Wilkins, 1986].

As a result of the success of its first term and the continued need for coordinated activities, a second term was granted to the IUGG/IAG SSG 5-98 in 1987. In addition to the goals of the first term, the group also undertook the task of encouraging and coordinating (when appropriate) the study of various techniques for forecasting atmospheric angular momentum (AAM) and Earth rotation by dynamical and statistical means. In addition, they also assumed the role of advisors to the Central Bureau of the IERS on the use of AAM in the new service [Dickey, 1992].

During its two terms, this SSG encouraged cooperative studies through the membership of scientists from a broad spectrum of the disciplines involved and provided a forum for discussion by having meetings in conjunction with relevant conferences and scientific meetings. An improved communication and data flow between the atmospheric and geodetic communities was established, with SSG 5.98 being the *de facto* data center during the 1983-1989 period. Interactions on models and applications were stressed; topics discussed included the implications of water storage on Earth rotation, the effect of the inverted barometer hypothesis and its limitations, the role of the oceans in the Earth's angular momentum budget, and the importance of orography model improvements. The SSG worked with meteorological data centers to obtain optimal atmospheric angular momentum (AAM) excitation functions as well as forecast fields and has advocated for the production of additional data sets such as atmospheric torque determination [White, 1991]. The use of both AAM analysis and forecasts has been demonstrated to be skillful [Rosen

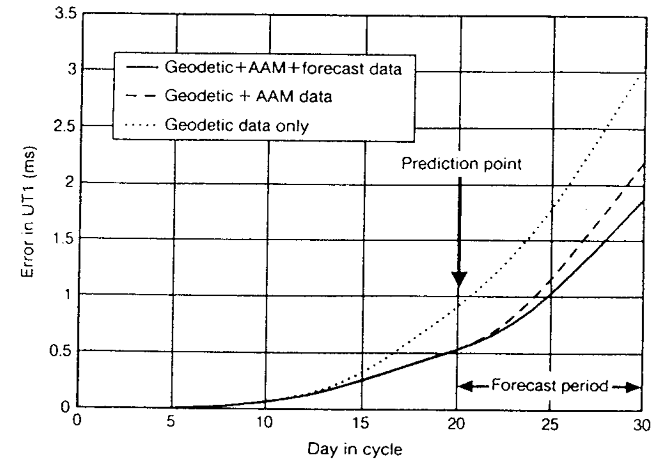

Fig. 5. Root-mean-square errors in Universal Time (UT1) for three forecast series using 45 cycles of 30 days each from 1987.0 to 1990.7. These results indicate how forecasts of Universal Time can be improved by including atmospheric angular momentum analyses and forecasts from global numerical prediction models; after Freedman and Dickey [1991].

et al., 1987 and 1991; Bell et al., 1991] and to improve Earth rotation predictions [see Fig. 5, Freedman and Dickey, 1991].

Based on the important role of AAM data in scientific analysis and its use in Earth rotation predictions, the IERS established in October 1989 a new sub-bureau for atmospheric angular momentum activities centered at the National Meteorological Center (USA), under the leadership of A. J. Miller. This sub-bureau is currently serving as the focus point for data exchange [Salstein et al., 1992].

IV. Advances in Analysis and Interpretation

A. *Universal Time (UT1) and Length-of-Day*

Comparison of astronomical measurements with axial atmospheric angular momentum first indicated the significance of the atmospheric contribution to Earth rotation. Various studies (e.g., Rudloff, 1973; Lambeck and Cazenave, 1977, and Lambeck and Hopgood, 1981) have related LOD fluctuations to changes in atmospheric angular momentum on time scales ranging from months to a few years using mean monthly or longer period atmospheric data. Hide et al. [1980], comparing the wind component of angular momentum evaluated at 12-h intervals from the First GARP Global Experiment (FGGE) with LOD data, demonstrated that angular momentum transfer between the solid Earth and the atmosphere could fully account for the observed LOD variation on time scales of days to weeks. Intercomparisons of AAM data with modern LOD data obtained from space geodetic techniques (see for example, Fig. 2) have been at the forefront of recent research on seasonal and sub-seasonal fluctuations in the Earth's angular momentum budget (for example, Langley et al., 1981; Rosen and Salstein, 1983; Carter et al., 1984; Eubanks et al., 1985a; Morgan et al., 1985 and Dickey et al., 1992b).

Changes in LOD at seasonal and higher frequencies can be attributed primarily to exchange of angular momentum with the atmosphere, with zonal frictional stress and surface pressure gradients acting as agents for transferring angular momentum between the atmosphere and the solid Earth. At the other end of the frequency domain, tidal dissipation, post-glacial rebound and core-mantle interactions are accepted as the causes of the long-term (secular to decade) variations in LOD. Intermediate between these regimes fall the interannual variations, defined here to be fluctuations with periods between one and five years. The amplitude of these variations (up to 0.5 ms) is comparable with that of the seasonal cycle, implying that the atmosphere could play a major role in their excitation.

Several earlier studies have attempted to link interannual LOD variations with the stratospheric Quasi-Biennial Oscillation (QBO—characterized by the regular alternation of the zonal wind in the equatorial stratosphere at periods that vary from 24 to 30 months) [for review, see Lambeck, Chapter 7, 1980]. Initially, Lambeck and Cazenave [1977] associated interannual LOD changes during the 1955-71 period with the QBO. Later, Stefanick [1982] proposed a connection between interannual LOD and the "Southern Oscillation" by establishing coherence between LOD and equatorial Pacific air temperature (whose fluctuation is a good index of the Southern Oscillation phenomenon), speculating that the coherence was caused by zonal wind anomalies originating in the tropics. The coupled El Niño/Southern Oscillation (ENSO) phenomenon involves large-scale redistribution of atmospheric mass between the eastern and western ends of the Pacific basin, and is associated with widespread changes in both atmospheric and oceanic circulation [Philander, 1990]. Further investigations were stimulated by the occurrence of the unusually strong and well observed El Niño of 1982-83 [see e.g. Philander, 1983, 1990; Rasmusson and Wallace, 1983]; the largest changes ever recorded in LOD and AAM occurred during this ENSO event (January and February, 1983) [Fig. 2—see also Rosen et al., 1984 and Eubanks et al., 1985b]. Various studies [Chao, 1984 and 1988; Eubanks et al., 1986; Dickey et al., 1990 and 1992c] have established significant correlations between interannual LOD and the Southern Oscillation Index (SOI), computed as the seasonally-adjusted difference of the sea-level pressure between Tahiti and Darwin, Australia. During an ENSO event, the SOI reaches a minimum, and there is a concomitant collapse of the tropical easterlies and an increase in χ_3. Conservation of total angular momentum requires the Earth's rate of rotation to diminish, causing LOD to increase. A further increase in AAM may result from the large-scale heating of the tropical troposphere associated with the El Niño events [Stefanick, 1982], leading to a zonally-symmetric rise in the tropical 200 mb height field [Horel and Wallace, 1981] and a consequent strengthening of the upper-level subtropical jet streams.

Recent studies [Rasmusson et al., 1990; Barnett, 1991, Keppenne and Ghil, 1991] have demonstrated that in addition to strong variability in the 3 to 7 year period range, the ENSO cycle is also characterized by a distinct quasi-biennial component. This bimodality is a common characteristic of LOD, SOI, and atmospheric angular momentum time series [Dickey et al., 1992a;

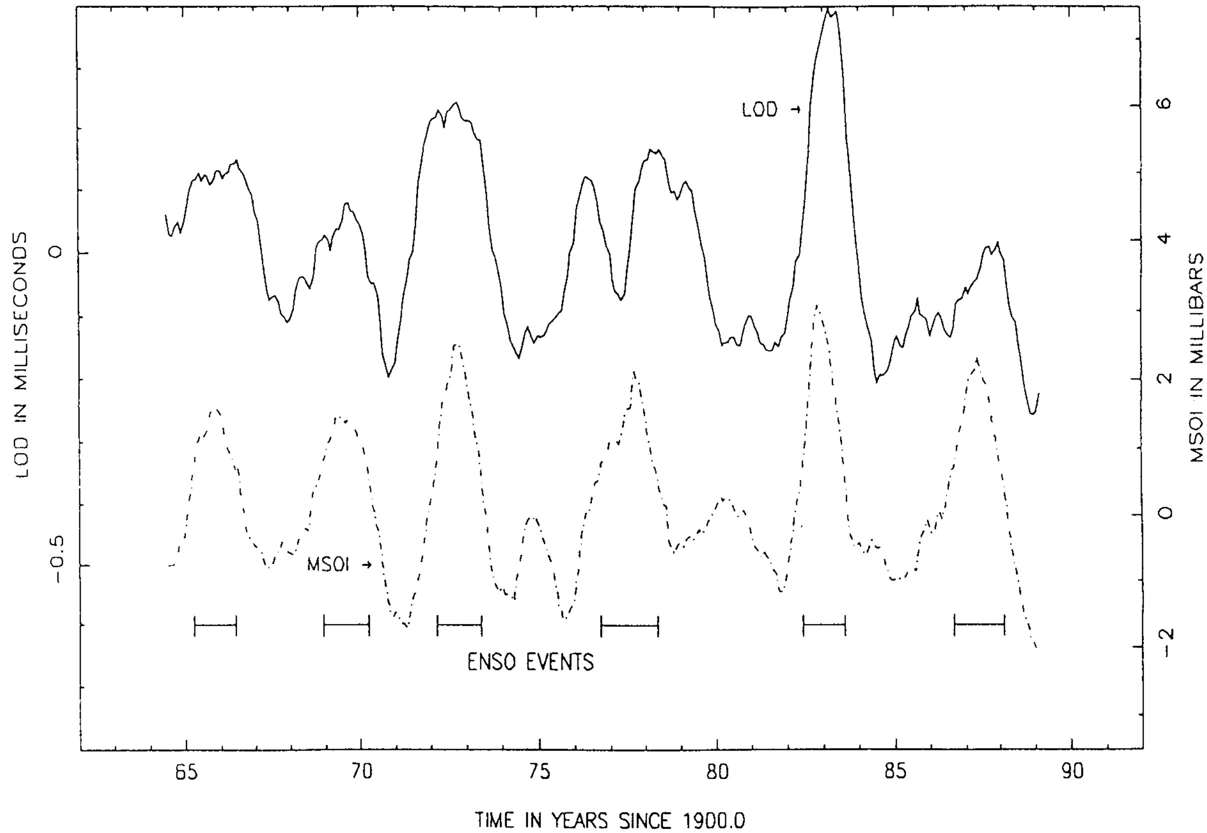

Fig. 6. The interannual LOD variation (solid upper line), compared to the Modified Southern Oscillation Index (dot-dashed). Both represent the difference between a one-year and five-year moving average.

Penland et al., 1991]. Hence, one must consider both the "conventional" ENSO variability as well as that associated with the QBO (both the tropospheric and the stratospheric components). Chao [1989] has demonstrated that independent measures of the QBO and ENSO cycles, when analyzed jointly, yield improved correlations with LOD.

The striking agreement between the interannual LOD variations and the MSOI [a modified Southern Oscillation index formed by taking the negative of the running annual SOI variation] is evident in Fig. 6 [Dickey et al., 1992c]. Similar comparisons have been made with data sets beginning in 1860 to ascertain if LOD can be used as a proxy index of interannual global wind fluctuations [Salstein and Rosen, 1986; Dickey et al., 1990 and 1992c]. Results indicate correlations are robust enough that LOD can be used as a proxy index beginning in about 1930 [Dickey et al., 1992c]. The maximum cross-correlation in the modern data (0.72) is found with the MSOI leading LOD variations (and the transfer of angular momentum to the solid Earth) by about 2 months. Atmospheric winds play the dominant role in these variations, accounting for up to 89% of the LOD variation in a case study of the 1982-83 El Niño [Dickey et al., 1992c]. The stratosphere is an important contributor, as it accounts for as much as an additional 20% in the LOD variance explained relative to the winds below 100 mb. The LOD variance not accounted for by AAM during the case study (64 μs rms) is comparable to the difference between interannual variations in data from the NMC and EC (18 μs rms), implying that "noise" in the AAM data may explain a substantial part of the residual. Additional sources of discrepancy include systematic AAM error and a possible oceanic contribution [Dickey et al., 1992c].

Changes in both the AAM and LOD contain a large seasonal cycle, dominated by annual and semiannual harmonics (Fig. 2). The seasonal cycle of angular momentum causes seasonal LOD changes with an amplitude of about 0.5 msec, and UT1 changes with an amplitude of about 30 msec. The annual angular momentum cycles in the two Hemispheres are nearly 180 degrees out of phase, with the Northern Hemisphere having a larger amplitude. The annual cycle is mostly due to changes in the mid-latitude westerly (i.e., eastward propagating) winds, particularly the subtropical jet streams at or near the 250 millibar level [Rosen and Salstein, 1983]. Various studies of the small apparent discrepancies found in AAM-LOD intercomparisons [Eubanks et al., 1985a; Morgan et al., 1985] reveal that imbalances occur in the angular momentum budget at the semi-annual period and to a lesser extent at the annual period. The seasonal imbalances can be attributed to the failure to represent contributions from stratospheric winds (up to the 1 mb level) satisfactorily in the routine operational analyses [Rosen and Salstein, 1985 and 1991].

Other geophysical processes, however, such as the effect of ocean circulation, should be included in detailed investigations of the Earth's angular momentum budget [Eubanks et al., 1985a; Brosche and Sündermann, 1985; Johns et al., 1987].

Superimposed on the annual cycle in both geodetic and atmospheric data is the irregular "intraseasonal" fluctuation, evident on time scales ranging from roughly 40 to 50 days (Fig. 2). The corresponding oscillations in zonal winds and other meteorological quantities were first discovered by Madden and Julian [1971, 1972] in station data from the equatorial Pacific. Since that time, higher-frequency oscillations have also been seen [Miller, 1974] and the 40 to 50 day oscillation has been observed on a global scale [Krishnamurti and Subrahmanyam, 1982; Yasunnari, 1981; Anderson and Rosen, 1983]. The corresponding Earth rotation changes were first detected in optical data [Zheng, 1979] and confirmed by their presence in four independent UT1 data types [Feissel and Gambis, 1980]; Langley et al. [1981] later reported this effect in both the AAM and LOD from lunar laser ranging. Feissel and Nitschelm [1985] showed the intermittent variability of this oscillation. The peak amplitude seems to be about 0.2 msec of length of day, though the oscillation exhibits changes in both period and amplitude on a year-to-year basis. Morgan et al. [1985] showed that any nonmeteorological contribution to the 40-50 day oscillation is not significantly larger than the uncertainties in the observations (about 0.06 ms).

Three possible mechanisms for the origin have been proposed. The so-called "Madden-Julian" mechanism connects these intraseasonal LOD and AAM oscillations to eastward-propagating anomalies in tropical convection and zonal wind [Madden, 1986 and 1987]. A second hypothesis [Ghil, 1987; Ghil and Childress, 1987] relates the oscillation to an instability of the nonzonal westerly flow caused by the interaction of the jet stream with mountains in the mid-latitudes. The dominant period of this instability in a simplified, equivalent-barotropic model of the atmosphere is near 40 days; however, for realistic parameter values, it has aperiodic, intermittent behavior, which would explain the broad-band nature of the AAM/LOD oscillations. The third mechanism, proposed by Simmons et al. [1983], links these oscillations to atmospheric disturbances which derive their energy from the basic state through barotropic instability. In this theory, topography contributes only to the maintenance of asymmetries in the climatological basic state, and is absent from the instability mechanism itself; in the second approach, topography interacts both with the basic flow and with its oscillatory instability.

The analysis of Earth rotation variations in concert with AAM data provides novel insights into the intraseasonal oscillation and other geophysical processes. Studies of the spectral characteristics of signal-to-noise ratios in both data types, for example, indicate that LOD determinations give a more accurate picture of 40 to 50 day variations in the global angular momentum budget than can be obtained at present from the available AAM determinations [Dickey et al., 1992b]. By compositing Earth rotation data over several years, the global intraseasonal oscillation was found to be strongest during Northern Hemisphere winter [Dickey et al., 1991]. These data indicate that the low-frequency variability of the Northern Hemisphere extratropics

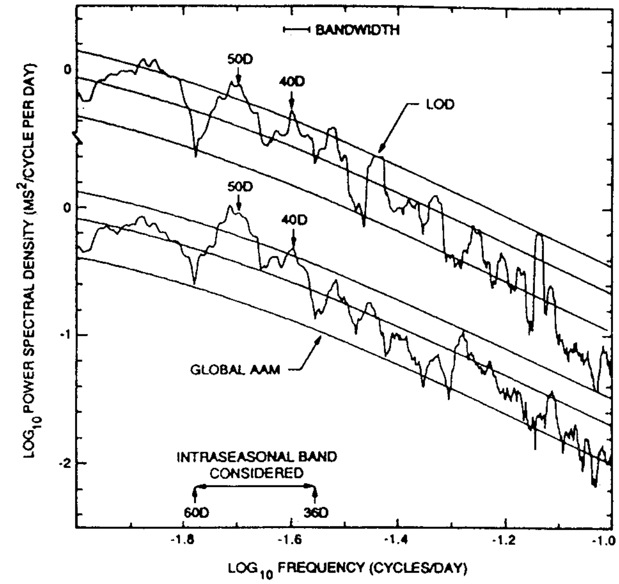

Fig. 7. Log-log power spectrum of LOD (top) as measured by space-geodetic techniques and (bottom) as inferred from NMC AAM data, for the period 1976 through 1988. Each is fitted to a first-order autoregressive model (middle smooth curves) with 95% confidence levels shown (upper and lower smooth curves). Significant peaks in the 36-60 day range are indicated. The bandwidth shown pertains only to the frequency at which it is plotted on this and subsequent log-frequency plots; after Dickey et al. [1991].

may be important to the dynamics of the global oscillation, as envisaged in the second and third hypotheses [Dickey et al., 1991; Marcus et al., 1990a and b]. Spectral analysis of modern LOD data shows the presence of two distinct intraseasonal oscillations, with periods near 50 and 40 days respectively (Fig. 7). Studies of concurrent AAM variations from the NMC operational analysis, and from perpetual-January runs with the UCLA General Circulation Model, indicate that the larger-amplitude 50-day oscillation arises in the tropics, whereas the 40-day oscillation originates in the Northern Hemisphere extratropics. Thus, comparisons of geodetically-determined LOD values with both observed and simulated AAM data indicate that the global intraseasonal oscillation may result from a combination of all three aforementioned mechanisms.

The elucidation of the relation between LOD and AAM at high frequencies is central to our understanding of the Earth's angular momentum budget and is currently an area of active research [Rosen et al., 1990; Herring and Dong, 1991 and Dickey et al., 1992b]. Significant coherence is found between the LOD and AAM at periods down to 8 days, with lack of coherence at shorter periods caused by the declining signal-to-measurement noise ratios of both data types [Dickey et al., 1992b]. In this study, the expected coherence was calculated as a function of frequency, using stochastic models of the geophysical processes involved and of the associated measurement errors (Fig. 8); the model provides a good fit for periods from 150 to 2 days, but higher accuracy and more frequent data are needed to resolve the exchange of angular

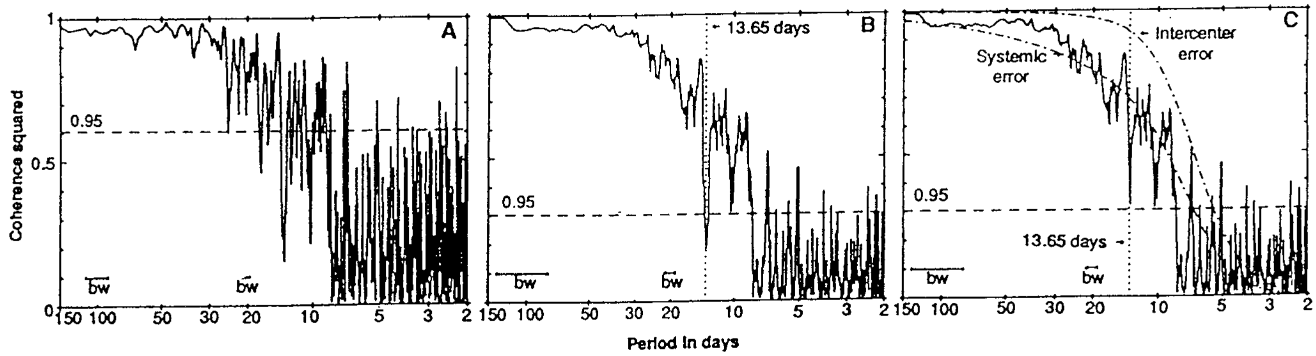

Fig. 8. (A). Coherence squared between LOD* as measured by space geodetic techniques, and that inferred from the combined *AAM* data, with a spectral smoothing of 5 (the Yoder et al. [1981] model has been used to remove the effect of LOD variations induced by the tides); (B) same as (A) except with a spectral smoothing of 11; (C) same as (B) except that the Brosche et al. [1989 and 1991] tidal model has been utilized. The curve labeled as "Intercenter error" shows the expected coherence between LOD and the combined AAM for the model of the AAM error spectrum based on the AAM pairwise differences; also shown is the expected coherence between the two series based on the combined AAM-LOD difference, labeled as "Systematic error"). Horizontal dashed line is 95% confidence level; bw is the bandwidth; after Dickey et al. [1992b].

momentum between the Earth and the atmosphere at shorter periods. Although no significant lags or leads at the few day level have been established (indicating little or no non-tidal oceanic contribution), the oceans, via barotropic waves, could contribute on short time scales (a few days or less) to the Earth's angular momentum budget [Ponte, 1990]. Comparison of AAM and LOD (or UT1–UTC changes) at higher frequencies could resolve the ocean's role and further elucidate our understanding of the interaction between the solid Earth and the atmosphere.

It is important to understand the various phenomenon that affect Earth rotation on shorter time scales. Diurnal and semi-diurnal rotational variations were postulated by Yoder et al. [1981], who proposed that such signatures should arise from the interactions of the ocean tides with the solid Earth. Estimates of these variations were made by Baader et al. [1983] for the M_2 tide and were refined by Brosche et al. [1989 and 1991] for the major diurnal

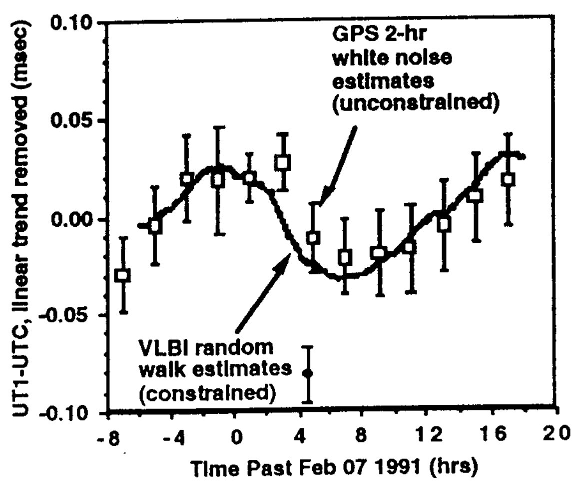

Fig. 9. Comparison of GPS and VLBI sub-daily estimates for UT1 variations (after Lichten et al., 1992, VLBI results provided by T. Herring).

and semi-diurnal tides. Herring and Dong [1991] used the approach of empirically fitting the major tidal components to sub-daily VLBI observations. Dickman [1992] developed the "broad-band" Liouville equation approach and determined the effects of the dynamic ocean tides on Earth rotation. Comparisons with the independent techniques of VLBI and GPS confirm the reality of a strong diurnal and semi-diurnal signature [~0.1 msec (5cm) in amplitude—see Fig. 9, Lichten et al., 1992a and b]. The geodetically-determined UT1R variations place constraints on oceanic tidal models [see Fig. 10, Dickey et al., 1992d]; results indicate excellent agreement with the models of Brosche et al. [1991] and Herring and Dong [1991]. Predicted diurnal variations from the Dickman model [1992] show significant correlation with the observational results, but are too small in amplitude.

B. Polar Motion

The influence of the atmosphere on polar motion has been less extensively studied than has its influence on the LOD; historically, the work that has been done concerned mostly with atmospheric excitation of the annual wobble and evaluating the role of the atmosphere in exciting the Chandler wobble (see, for example, Lambeck, 1988 and Eubanks, this volume, for a review). Recently, however, considerable effort has been made in investigating rapid polar motion variations that are primarily driven by the atmosphere [Eubanks et al., 1988 and Gross and Lindqwister, 1992a and b]. This section will briefly highlight recent advances in atmospheric excitation of polar motion; the reader is also referred to parallel articles in this volume by Eubanks and Wilson.

The atmosphere and oceans, together with the effect of variable ground water storage, are clearly responsible for exciting a large portion of the annual wobble [Merriam, 1982; Wahr, 1983; Chao and Au, 1991b and Kuehne and Wilson, 1991]. However, the entire annual wobble is not fully accounted for. The Chandler wobble is a free oscillation of the Earth [Smith and Dahlen, 1981; Wilson and Vincente, 1980] whose source of excitation is uncertain. Since polar motion is assumed to be a linear response

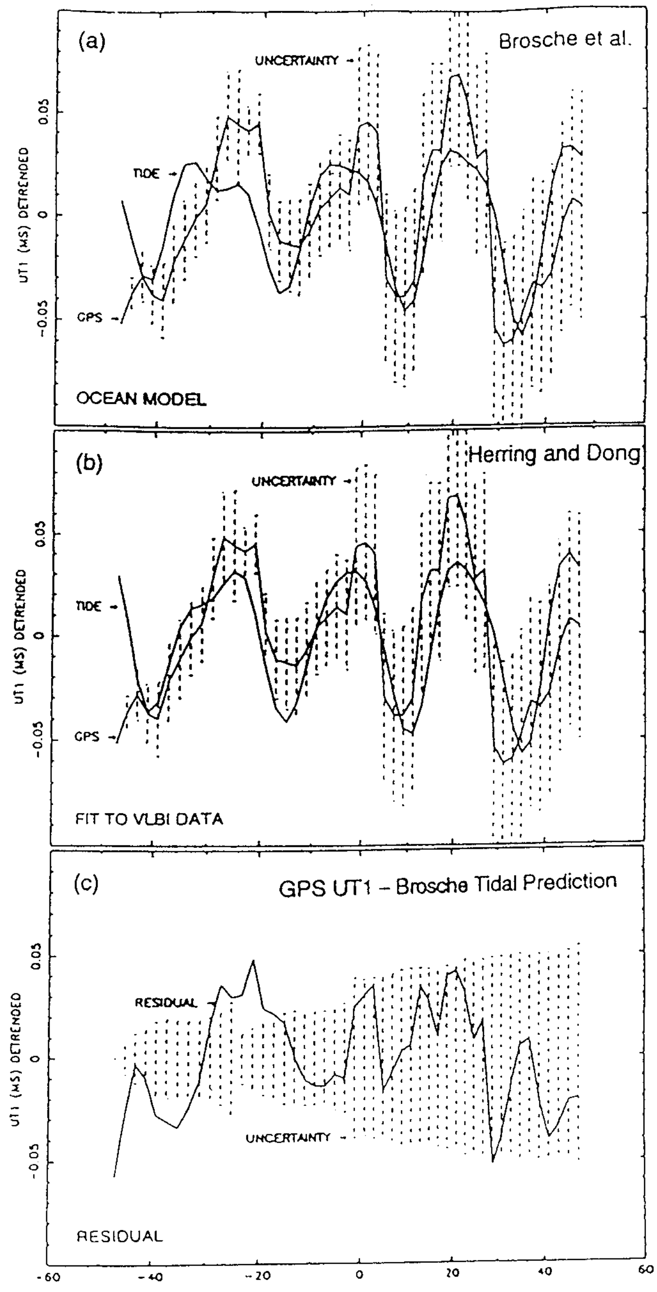

Fig. 10. Sub-daily UT1 Variations: (a) Comparison between GPS determinations and predictions from the Brosche et al. [1991] oceanic tidal model; (b) comparison between GPS determinations and predictions from the Herring and Dong [1991] empirical tidal model, derived from a fit to VLBI data; and (c) residual between the GPS determination and prediction obtained from the Brosche et al. [1991] tidal model. In all three figures, the dashed lines indicate the uncertainty associated with the GPS determinations; after Dickey et al. [1992d].

to geophysical excitation, the problem is to find an excitation source with enough power near the Chandler period of about 433 days. The major candidates are the atmosphere and the redistribution of ground water. Other proposed sources, such as earthquakes, are probably too small in magnitude [Gross, 1986].

In a recent work, Chao and Au [1991b] have focused on excitation of the Earth's annual wobble for the period from 1980 to 1988, utilizing both the wind and matter atmospheric excitation terms (see Eqn. 1) from the European Centre for Medium Range Weather Forecasts; calculations were done with and without the inverted barometer (IB) hypothesis. The wind term was found to contribute significantly to the total excitation. Dividing polar motion into a prograde and retrograde term, the analysis reveals that the IB has a small impact on the excitation of the prograde term and a considerable effect on the retrograde motion. Comparison of the better determined prograde term with LAGEOS satellite laser ranging polar motion results indicates that the amplitudes are nearly equal, but a large phase discrepancy exists between the geodetic and atmospheric results, pointing to a need for an additional source of excitation.

In a parallel study, Kuehne and Wilson [1991] investigated the effect of water storage in combination with air mass redistribution on the observed excitation of polar motion near the annual and Chandler frequencies for the period 1900-1985. They conclude that there is a discrepancy in accounting for more than half the variance of polar motion across a broad range of frequencies, suggesting a source of polar motion excitation due to air and water motion which has either not been correctly estimated or is not yet identified.

Turning to rapid polar motion variation studies, Eubanks et al. [1988], comparing observed χ-functions derived from geodetic observations with theoretical χ-functions derived from atmospheric data, demonstrated the existence of rapid polar motions with peak-to-peak variations of approximately 2 to 20 mas, fluctuating on time scales between two weeks and several months (Fig. 4). These variations are only partly accounted for by atmospheric surface pressure changes and, like the Chandler and annual terms, require an additional source of excitation. The "missing" excitation may be explained by errors in the data sets used (in either the polar motion series or the AAM series), by oceanic angular momentum, or possibly by groundwater redistribution.

Daily polar motion values determined from observations acquired during the GIG'91 measurement campaign (GPS IERS and Geodynamical Experiment), held from January 22, 1991 to February 13, 1991 [Herring et al., 1991 and Lindqwister et al., 1992] permit an unprecedented high time-resolution investigation of the effect of the atmosphere in rapid polar motion variations [see Fig. 11, Gross and Lindqwister, 1992a and b]. The wind and pressure terms are found to be of comparable importance in exciting the observed polar motions during this period with somewhat better agreement seen with the application of the inverted barometric approximation. Correlations as high as 0.88 are obtained between the observed polar motion and the AAM-induced series with AAM variations explaining as much as 74% of the variance of the observed polar motion (Fig. 11). Thus, the atmosphere appears to be the dominant polar motion excitation source during the GIG campaign [Gross and Lindqwister, 1992a and b].

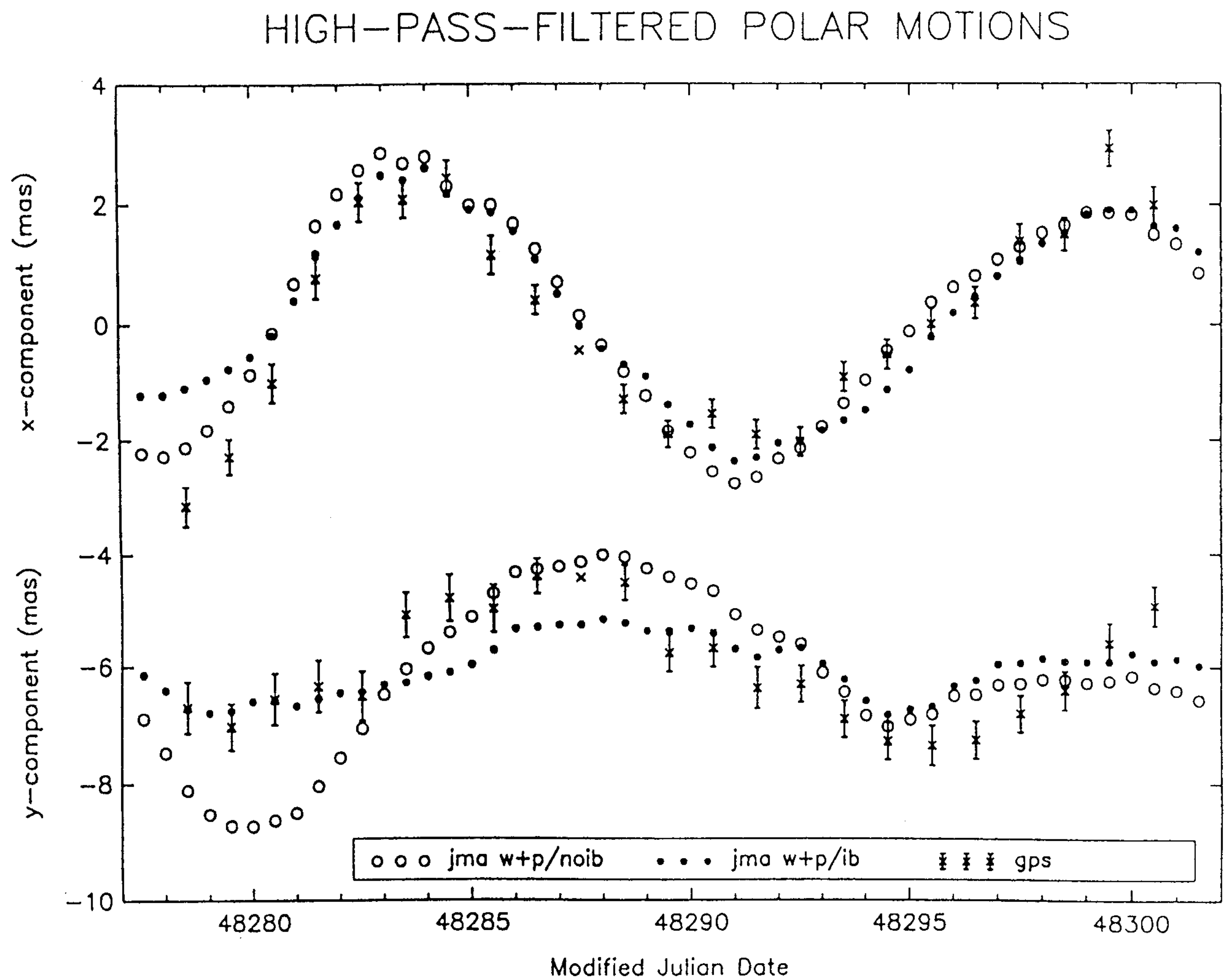

Fig. 11. The x-component (top) and y-component (bottom) of the observed and Japanese Meteorological Agency (JMA) AAM-induced polar motion series (both series have been high-pass-filtered using a cutoff period of 23 days). The crosses with error bars represent the observed series (one data point is plotted without error bars indicating that it is the interpolated point). The open circles represent the polar motion series induced by the JMA AAM χ-functions formed by summing the wind term with the pressure term computed under the rigid ocean approximation. The filled circles represent the polar motion series induced by the JMA AAM χ-functions formed by summing the wind term with the pressure term computed under the inverted barometer approximation; after Gross and Lindqwister [1992a].

V. Summary and Prospects for the Future

The new space geodetic techniques have had a profound influence on Earth rotation and polar motion studies. Typical uncertainties resulting from conventional optical observations were at the 1 ms level for Earth rotation and 10 mas for polar motion. Today's uncertainties have decreased dramatically by considerably more than an order of magnitude, in some cases approaching two orders. Independent VLBI networks have shown rms differences of ~0.3 mas for polar motion and ~0.02 ms for UT1 determinations [Eubanks et al., 1991]. Results from the ERDE (Extended Research and Development Experiment—Clark et al., 1990) have statistically determined standard derivations of 0.1 mas for polar motions and ~0.01 mas for UT1; however, it should be stressed that these are purely statistical in nature [Herring and Dong, 1991]. These advances have been accompanied by improvements in measurements and numerical models of the Earth's global atmosphere, which are used to calculate the atmospheric angular momentum and other synergistic atmospheric data sets.

Here, we have highlighted recent advances in the measurement and interpretation of Earth orientation and atmospheric excitation estimates. International cooperation through organizations such as MERIT, the IERS and the IUGG/IAG Special Study Group 5-98 (Atmospheric Excitation of the Earth's Rotation) was stressed.

The comparison of Earth orientation and atmospheric results is leading to a better understanding of the coupling of various components of the Earth system, especially among the solid Earth, the atmosphere and the oceans. Fluctuations in Earth rotation (UT1 and LOD) over the time scale of five years or less are dominated by atmospheric effects, with the wind term being most prominent. The agreement between the length of day and the meteorological χ_3 data is excellent. Yet, as old questions become answered, new ones arise. One example is the mechanism of the intraseasonal 40-50 day oscillation and the relationship between the tropical Madden-Julian oscillation centered at ~50 days and an oscillation centered at 40 days arising from the interaction of the jet stream with orography.

In contrast, many fundamental issues remain unresolved in polar motion studies; it is difficult to account for the full polar motion excitation source across the entire frequency band discussed here (from a few weeks to the Chandler period). The atmosphere and oceans, together with the effect of variable ground water storage, are clearly exciting a large part of the annual wobble; however, the entire annual wobble is not fully accounted for. The source of the Chandler wobble remains an open question; the major difficulty is to identify an excitation source with enough power near the Chandler period. Highly accurate and temporally dense measurements have enabled the discovery of rapid polar-motion variations, with peak-to-peak variations of ~2 to 20 mas, fluctuating on time scales between two weeks and several months. These variations are only partly accounted for by atmospheric wind and surface pressure changes and, like the Chandler and annual terms, require an additional source of excitation.

The future is even more promising with the anticipated technological advances envisaged for space geodesy and developments that are being planned in related areas. The availability of accurate Earth rotation and polar motion data along with AAM results and other ancillary data, such as torques, and their coupled analyses are keys to unraveling the causes and implications of Earth orientation changes. The continual improvement in the accuracy and density of data from the new techniques will allow the study of the Earth's exchange of angular momentum with its fluid envelope over even shorter time scales. High time-resolution measurements of Earth rotation and atmospheric angular momentum (AAM) and their interpretation has been proposed as a major research area for the 1990s, both by the workshop held at Erice in 1988 on the "Interdisciplinary Role of Space Geodesy" [Mueller and Zerbini, 1989] and by the NASA Workshop on Geodynamics and Geology held in July 1989 to plan NASA Solid Earth Science Programs for the coming decade [NASA, 1991]. The NASA Crustal Dynamics Project VLBI group at Goddard Space Flight Center conducted a first Extended Research and Development Experiment (ERDE) in October, 1989 designed to obtain high time-resolution measurements of the Earth's orientation by the VLBI technique and to test improvements in the VLBI measurement system [Clark et al., 1990]. These special sessions resulted in many cases in sub-hourly measurements and serve as a prototype for future efforts.

A special measurement campaign, SEARCH'92 (Study of Earth-Atmosphere Rapid Changes), is planned for Summer of 1992 (June 21-September 22, 1992) in conjunction with the GPS experiment sponsored by the International GPS Service; the coordination will be effected through the IERS [Dickey, 1991]. The campaign will involve all space geodetic techniques and obtain the best available complementary geophysical oceanographic and atmospheric data. A joint International Association of Geodesy/International Astronomical Union (IAG/IAU) Special Study Group, Rapid Earth Orientation Variations, has been formed to (1) interface with the IERS in the determination of rapid variations in Earth rotation by the space geodetic techniques; (2) advocate for the best possible auxiliary data from geophysical, oceanographic and atmospheric sources; (3) encourage improvements in measurement techniques (including geodetic, atmospheric, oceanographic and geophysical); and (4) encourage cooperative multidisciplinary studies. Special efforts are under way to obtain 6-hourly AAM determinations as well as the routine calculation of atmospheric torques.

The scientific benefits to be obtained from this campaign include increased understanding of the properties and origin of short-period fluctuations in the Earth's orientation, improvements to the tidal model at sub-monthly periods, and improved ability to predict changes in the Earth's rotation up to a month in advance. Our goal here is to observe and understand the interactions of the atmosphere and ocean with the rotational dynamics of the Earth, and their contributions to the excitation of Earth rotation variations over time scales of hours to months. At these frequencies, a number of geophysical processes are thought to be capable of affecting the Earth's rotation, including atmospheric wind and pressure changes, oceanic current and sea level changes, oceanic and solid Earth tidal motions, and seismic motions. High-frequency measurements, and complementary analyses, can be expected to lead to delineation of short-period tidal, atmospheric, oceanic, and seismic effects on length-of-day (LOD) and polar motion. These in turn will improve our understanding of broad-band wobble excitation processes, fluid-core resonance characteristics, and mechanisms of oceanic/atmospheric coupling to the solid Earth. In particular, the Earth's angular momentum budget (both axial and non-axial) can be examined at high frequencies. A comparison of AAM and LOD at these high frequencies (see Section 4) could uncover the ocean's role and further elucidate our understanding of the interaction between the solid Earth and the atmosphere. This would allow the role of atmosphere and oceans in the Earth orientation variations at high frequencies to be quantified. The appropriateness of the inverted barometer approximation at high frequencies could be investigated, and the respective roles of mountain torque and wind stress in the interaction between the solid Earth and atmosphere could be examined.

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